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Femtosecond Yb:YCOB laser pumped by narrow-stripe laser diode and passively modelocked using ion implanted saturable-absorber mirror

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The authors present, what they believe to be, the first femtosecond Yb:YCOB laser, pumped by a low-power, narrow-stripe laser diode. To facilitate modelocking, high-energy oxygen ion implantation of the saturable absorber is employed. 210fs pulse generation at 16mW average output power for 140mW incident pump power is reported.

Recently, we reported on the possibility of using low-power, narrow-stripe AlGaInP laser diodes as the pump source for femtosecond Cr:LiSAF lasers [1]. This is a low-cost alternative to high-power broad-stripe laser-diode pump sources since the power available from narrow-stripe devices, though lower, is used more efficiently owing to their near-diffraction-limited beams. This technique may be appropriate to laser systems for which higher power narrow-stripe laser diodes are available, e.g. 1 μm ytterbium based lasers pumped at the zero-phonon line near 976 nm. In this spectral region, narrow-stripe InGaAs laser diodes are available with powers as high as 200mW.

One promising ytterbium host which has recently received interest is the calcium rare-earth oxoborate matrix (i.e. $Ca_4YO(BO_3)_3$ (YCOB) or $Ca_4GdO(BO_3)_3$ (GdCOB)) [2]. Its strong crystal field minimises the quasi-three-level behaviour of Yb (due to the large splitting of the ground state) and broadens the emission band permitting ultrashort pulse generation. As a potential medium for the development of an efficient, low-cost, low-power laser system, Yb:YCOB appears to be very promising: when pumped at the zero-phonon line at 976 nm, the quantum defect is less than 7% [2] and its gain-cross-section upperstate-lifetime product is four times larger than Cr:LiSAF and ten times that of Yb:glass.

Unfortunately, the small gain-cross-section and long upperstate-lifetime of Yb:YCOB contribute to a high threshold for stable continuous wave (CW) modelocking [3]. Although a 90fs Yb:GdCOB laser was recently reported [4], it used a semiconductor saturable absorber mirror as the modelocking device which incorporated an absorber grown at low-temperature to increase defects and hence reduce the absorber recovery time [3]. Because this device was prone to damage by a Q-switching Yb laser, our present work has concentrated on using saturable Bragg reflectors (SBR) grown at optimum temperature. These have high damage thresholds due to few defects but hence have a long absorber recovery time. This further increases the threshold for CW modelocking.

In this Letter we report on a first experiment to assess the feasibility of modelocking an Yb:YCOB laser system pumped by one narrow-stripe laser diode. Ion implantation of a metal-organic chemical vapour deposition (MOCVD) grown SBR is utilised to increase the defect concentration and hence reduce the absorber recovery time to facilitate modelocking. This post-growth defect enhancement approach offers the possibility of 'tailoring' SBR absorbers to specific applications.

Fig. 1 shows a schematic diagram of the cavity used, which is similar to the laser from [1]. The folding mirror through which the pump was focused (M1) was operated close to normal incidence. The astigmatism from the Brewster cut gain medium was compensated by the larger angle of the short arm folding mirror (M2). This allows tight focusing on the pumped end of the Brewster-cut rod. For optimised CW pumping and subsequent adaptation to SBR assisted modelocking, the long arm of the cavity was set to ~1.5m and the short arm to 10cm. This created a beam waist on the end of the short arm of ~17μm suitable for tight focusing onto a SBR, and a waist of 29μm × 17μm in the gain medium.

The available gain medium was a 4mm long Brewster cut crystal with 15% Yb, having a maximum pump absorption coefficient of 6cm^{-1} at 976nm. No active cooling was employed.

The pump source was a single, narrow-stripe InGaAs laser diode supplied by Uniphase, rated at a maximum output power of 180mW at 976nm with a spectral width of < 1mm. The emitting aperture was ~3μm × 1μm, giving a near-diffraction limited, though asymmetric, beam. 6.2mm aspheric and 7.5cm plano-convex lenses served to collect and focus the beam into the gain medium. No reshaping of the asymmetric beam was performed.

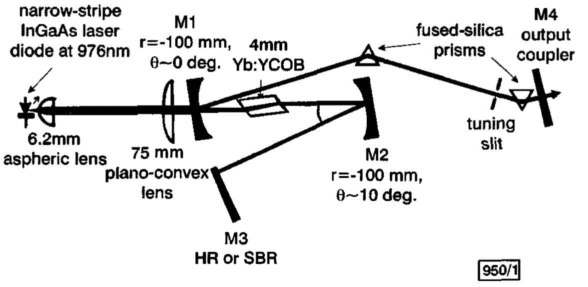

Fig. 1 *Schematic diagram of low-threshold modelocked Yb:YCOB laser (not to scale)*

The use of diffraction limited laser diodes offers two advantages compared to higher power broad-stripe devices. First, the superior beam quality allows increased gain saturation by permitting much tighter laser and pump focusing while maintaining excellent laser-pump mode overlap. This reduces the threshold for CW modelocking. Secondly, the narrower emission spectrum has an enhanced overlap with the narrow (2.3nm FWHM) zero-line absorption band at 976nm for a higher effective pump absorption coefficient.

For passive modelocking, a MOCVD grown SBR was utilised comprising a 10nm-thick InGaAs quantum well, situated in the middle of the top GaAs layer of a GaAs/AlGaAs Bragg mirror stack. As grown, this structure contained few defects and hence had a long absorber recovery time [3]. To shorten this subsequent to growth, a strip of this SBR was subjected to high-energy ion bombardment [5]. Nickel (Ni) and oxygen (O) ion bombardment was performed at energies of 12MeV and 9.5MeV respectively, both to a density of 10^{12} cm^{-2}. This was expected to increase the defect density of the absorber and hence reduce the absorber recovery time. Unlike low-energy ion implantation techniques which have been previously reported to successfully reduce the recovery time of saturable absorbers by implanting defect species directly into the absorber layer [6], high-energy ions pass straight through this layer, finally stopping within the Bragg mirror/substrate, leaving behind a trail of defects. This technique has been successfully demonstrated in InGaAs multiple quantum well absorbers for pulse cleaning in telecommunications applications [5]. We believe this to be the first application of high-energy ion implantation to a saturable absorber on a mirror structure.

Initially, the laser was aligned with all HR coated mirrors and optimised for a low CW threshold. Laser oscillation was achieved for incident pump powers below 12mW. After re-alignment at the maximum incident pump power of 150mW, the optimum output coupling of 1% gave an output power of 45mW, a slope efficiency of 37% and a corresponding threshold of 35mW. These are encouraging first results considering that the long free-running wavelength of 1050nm indicates re-absorption loss at shorter wavelengths and is evidence that this gain medium is too long.

For modelocked operation, M3 was replaced by the implanted SBR. The CW laser output power with a 1% output coupler fell from 45mW (with HR mirror) to 39mW for the O implanted sample but down to 11mW for Ni indicating that high-energy Ni implantation had significantly increased the nonsaturable losses of the SBR. No modelocking was subsequently observed with the Ni implanted sample.

Dispersion compensation, provided by two low loss fused-silica prisms separated by 67cm, permitted femtosecond soliton modelocked operation. Using the O implanted SBR, CW modelocked operation was readily obtained at maximum pump power by tuning the laser through the absorption band edge near 1050nm; however, it was characterised by a broad, multiple lobed, unstable spectrum indicating multiple pulsed modelocked behaviour. Further optimisation of the prism glass insertion, pump power reduction and realignment of the cavity permitted stable, single pulsed modelocked operation at a repetition rate of ~85MHz. A pulse duration of 210fs was deduced from the intensity autocorrelation in Fig. 2*a* assuming a sech^2 profile. The corresponding spectrum in Fig. 2*b* verifies the pulses to be near-transform limited ($\Delta\nu\Delta\tau$ = 0.3) with a central wavelength of 1052nm. The modelocked output power was 16mW through a 1% output coupler for 140mW incident pump power. Increasing the pump power and realigning the cavity for maximum output power resulted in unstable multiple pulsed operation. With further optimisation of this cavity, higher modelocked output powers and shorter pulse durations should be possible.

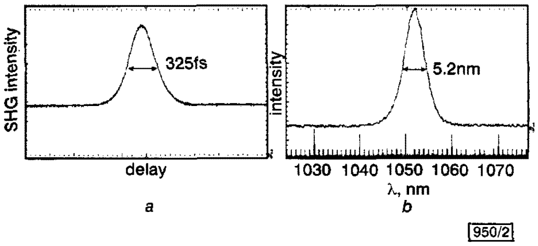

Fig. 2 *Temporal and spectral characteristics of 210 fs pulses*

a co-linear intensity autocorrelation
b corresponding spectrum

Using an unimplanted SBR allowed the importance of the implantation to be qualitatively assessed. Unlike the implanted sample, strong Q-switched behaviour predominated as the laser was tuned through the absorption band. With great difficulty, only unstable, multiple pulse modelocking was briefly observed; no stable single pulse modelocking could be achieved for any output power, indicating clearly that implantation was crucial for the modelocking of this Yb:YCOB laser system. Of course, further investigations into the effects of the high-energy implantation on the absorber dynamics as well as optimisation of the implantation level for modelocking will need to be carried out.

In summary, we have demonstrated, for the first time to our knowledge, a femtosecond Yb:YCOB laser. A narrow-stripe laser diode provided the pump power and modelocking was established using an ion-implanted SBR. High-energy ion implantation has been utilised for the reduction of the absorber recovery time to facilitate modelocking of gain media with very high gain saturation intensities. Optimisation of the intracavity dispersion is expected to further reduce the pulse durations generated by this modelocked laser. Although a reduction of the gain medium length will improve the CW performance reported, this work has shown the approach of using lower power, but superior beam quality, narrow-stripe InGaAs laser diode pump sources to be very promising for femtosecond Yb based lasers.

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